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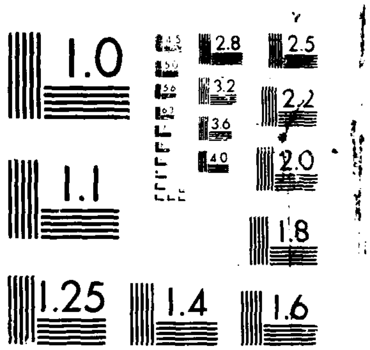

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SOLID-STATE EYESAFE LASER SYSTEMS IN THE 1.5 - 2.1 MICROMETER REGION

H. Lee Pratt
Advanced Sensors Directorate
Research, Development, and Engineering Center

JUNE 1987

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35898-5000

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Solid-state laser materials for the eyesafe region of 1.5 - 2.1 micrometers are reviewed. Laser materials include erbium and holmium in a variety of hosts, as well as Raman shifted lasers. Compatible detectors, including Ge, InGaAs, and InGaAsP, are reviewed. Several commercial and military applications are identified.

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CONTENTS

I. INTRODUCTION

Solid-state lasers represent an important class of laser devices with many applications in communication systems, rangefinding, military target designation, materials processing, product marking, and a host of other uses. Here the term "solid-state" defines a solid (as opposed to gas or liquid) laser medium, usually in a cylindrical rod or rectangular slab configuration, composed of a crystal or glass host material in which the lasing element is embedded. (The term "semiconductor laser" is applied to laser diodes, rather than the term "solid-state", in contrast with its conventional usage in electronics.)

Solid-state lasers include the very first laser, the ruby laser demonstrated in 1961 by T. H. Maiman. Indeed, early work in the ensuing years on neodymium, erbium, holmium, and other rare earth laser elements forms the basis of the present subject. But except for ruby and neodymium lasers, very few practical applications for these early materials have developed with any subsequent commercial or military production on a large scale.

In recent years there has been a significant increase in the development of solid-state lasers. A number of advances have led to this renewed interest:

- the development of slab and thin plate laser medium geometries for better thermal control
- improved laser glasses with better homogeneity and thermal properties
- new sensitized laser crystals (such as GSGG) with increased efficiency
- larger, better quality crystal boules from several competitive sources
- the promise of efficient laser diode pumping as opposed to conventional flashlamps
- nonlinear techniques (e.g. Raman scattering) to generate additional spectral lines
- tunable solid-state lasers
- nonlinear techniques to improve beam quality (e.g. phase conjugation techniques)

A. Requirements for Eyesafe Lasers.

This report addresses advances in solid-state laser materials which, either directly or by efficient frequency conversion techniques, are particularly suitable for eyesafe applications in long range communication systems. Such applications include rangefinding, surveying, and other single-path or double-path systems for which a pulsed laser may be most effectively employed.

Eye safety is of particular importance when the operational path of the laser extends over several kilometers in length. In such situations it is not always possible nor practical to control unintentional entry into the laser path. The potential for ocular damage, although perhaps statistically remote in occurrence, must be contended with in order to make acceptable the usage of the laser system.

The neodymium and ruby laser systems currently in wide usage, particularly in military systems, are a case in point. Both lasers are considered significant eye hazards at their normal output power levels. Elaborate procedures and accessory equipments have been developed to preclude the possibility of accidental exposure and possible eye damage during training engagements and other field situations. Techniques that are being employed include all of the following;

- o laser protective eyewear
- o attenuated laser power levels
- o beam spreading techniques for lower flux levels
- o reduced pulse repetition rates
- o simulation by low-power semiconductor lasers
- o restricted access to operational areas
- o limited usage of lasers when the above techniques are not possible.

As a result of all the restrictions on laser usage, requirements for laser systems operating at more eyesafe wavelengths have been in existence since the 1960's. However, these requirements have gone largely unmet by solid-state lasers. The ruby and neodymium lasers, even as inefficient as they are, have proven far superior to similar but longer wavelength lasers. Neodymium lasers teamed with silicon photodetectors have resulted in a transmitter/receiver couple that has been vastly superior to the less efficient lasers and much less sensitive detectors in the spectral region above 1.5 μm.

Yet this situation is changing. Laser materials are improving with better quality crystal and glass hosts, codoping for improved efficiency, and superior coating designs. Nonlinear frequency conversion techniques can now efficiently change an established but hazardous laser device into one whose output beam is eyesafe. In addition, a new generation of photodetector materials are rivaling silicon in sensitivity, yet peak in performance at wavelengths longer than possible with silicon. The desire for eyesafe laser systems can now be met for some (but not all) applications without excessive penalties in performance, weight, power consumption, or cost.

B. Laser Safety Standards

In the United States the American National Standards Institute provides the Z136.1 laser safety standard [1] that has been widely accepted. The military services have developed similar guidelines, such as the U. S. Army's TB MED 524 [12]. These and other safety references give recommendations for limits on exposure levels for various lasers as a function of wavelength, pulse width, pulse rate, exposure time, and other parameters.

The maximum permissible exposure (MPE) value or protection standard is often specified. This is a value that is below all known hazardous levels and includes a safety factor which allows for individual differences and experimental uncertainties. Different levels are given for skin exposure, intrabeam viewing, extended optical sources, single pulse exposures, and multiple pulse exposures. Table 1 lists protection standards for several typical laser wavelengths. Note that wavelengths above 1.4 μm are considerably safer than shorter wavelengths. Note also that 1.54 μm wavelength has been designated as especially safe, by a factor of 100, compared to other wavelengths in the same spectral region.

TABLE 1. Laser Safety Ocular Protection Standards

(Maximum Permissible Exposure Levels)

Laser	Wavelength, μm	MPE, J/CM^2	
		Single Pulse	10 Hz
Ruby	0.6943	5×10^{-7}	
Nd:YAG	1.06	5×10^{-6}	1.6×10^{-6}
Er:Glass/Raman	1.54	1	2.1×10^{-1}
Er:YLF	1.73	1×10^{-2}	2.1×10^{-3}
Ho:YLF	2.06	1×10^{-2}	2.1×10^{-3}
All Others	1.4-1000	1×10^{-2}	2.1×10^{-3}

Assumption: All pulsewidths are 20 ns.
All values are based on data in references 1 and 12.

II. ERBIUM AND OTHER SOLID-STATE LASERS

Only a few solid-state materials presently deserve serious consideration for eyesafe laser sources in the 1.5 to 2.1 μm spectral region. Significant features of each of these are reviewed in the following sections.

A. Solid-State Laser Materials

The most widely accepted laser dopant for crystalline and glass solid-state lasers has been neodymium. First reported as a lasing medium in glass and then calcium tungstate hosts, its superiority to other laser systems has been clearly demonstrated particularly in the host material yttrium aluminum garnet, or YAG. The composition of YAG, Y3Al5O12, is a synthetic garnet that has proven to be stable and hard with good optical and thermal properties that permit moderate to high average and peak power levels. Various glass host materials have also proven acceptable for neodymium lasers, as have yttrium ortho aluminate (YAlO3), yttrium lithium fluoride (YLiF4), gadolinium scandium gallium garnet (known as GSGG) and at least forty other materials [19].

There are a number of lasing transitions possible for neodymium in the various laser hosts, but almost all transitions lie in the 0.94 to 1.35 μm spectrum. The lowest threshold lasing line is at 1.06 μm in Nd:YAG, and maximum gain in many other hosts is usually between 1.05 and 1.07 μm. It has not been possible to obtain an eyesafe (i. e. longer than 1.4 μm) lasing transition in neodymium that is efficient and does not require cryogenic cooling of the laser crystal.

Neodymium may be the most important lasing medium in solid-state lasers, but other trivalent elements have also been extensively investigated. The ruby laser, which was first to demonstrate laser action in the form of Cr^{3+}:Al2O3, has been a major source for pulsed laser radiation in the far red portion of the visible spectrum. Its use, however, has been primarily discontinued in favor of more efficient lasing transitions.

In addition to neodymium, the rare earth lasing elements include erbium, holmium, thulium, praseodymium, gadolinium, and others [19]. Of these, however, only erbium and possibly holmium have shown much potential for widespread application.

B. Erbium Lasers

Particularly for its eyesafe characteristics, the material erbium has continued to be investigated since 1962. Indeed, the pace of research in erbium lasers has picked up in recent years and new transitions have been reported as recently as the past year.

Like neodymium, erbium has been used as the lasing medium in a number of glass and crystalline hosts. At least three hosts (glass, YAlO3, and YLiF4) have proven most important and each produce lasing lines that are in the eyesafe region between 1.5 and 2.1 μm.

Erbium doped glasses produce a popular wavelength near 1.54 μm, with transitions between the $^4I13/2$ state and the $^4I15/2$ ground state of Er^{3+} [19]. Both phosphate and silicate glass hosts have been used. This transition is attractive for a number of reasons. At this relatively short wavelength many of the common optical materials for lenses, prisms, windows, beamsplitters, etc. may be utilized. However, there are some limitations to polarizers, Q-switches, and coatings.

The 1.54 μm wavelength also exhibits a very excellent rating for eye safety from the scientific and medical community. The MPE level (single pulse) is the very large value of one joule per square centimeter. The MPE is 0.21 joules per square centimeter at a pulse rate of 10 Hz for pulsewidths 20 ns wide (see Table 1). Other wavelengths in this same spectral region do not enjoy nearly as good a safety rating. (Other nearby wavelengths may be just as "safe" from a medical standpoint, but have not been so rated because of a paucity of experimental evidence where no good laser lines exist.)

From a systems viewpoint, cryogenic cooling of the laser medium is always undesirable. Erbium glass lasers operate without cooling, but not nearly as efficiently as Nd:YAG. At room temperatures the terminal lasing levels in Er:glass are partially populated, and so it acts somewhat in a three-level scheme with a high threshold for the onset of lasing. The same situation exists for erbium lasers in calcium tungstate (CaWO4), calcium fluoride (CaF2), and YAG hosts, at wavelengths between 1.5 and 1.6 μm, with corresponding high thresholds and low efficiencies.

Some significant improvements in efficiency are possible by "sensitizing" or codoping the crystal or glass with more than one impurity. The "sensitizer" ion is an additional impurity that absorbs some of the pump energy. It then transfers this energy to the lasing media via either light emission or a nonradiative energy coupling process. The ion receiving the energy, known as the "activator", then lases with an efficiency greater than possible without the codopant [20].

Ytterbium and neodymium have both been employed as sensitizers in erbium lasers. The additional impurity absorbs the pump light, usually from a flashlamp source, in spectral regions where the erbium is relatively transparent. This sensitized flourescence technique has been used in several host materials for erbium, including YAG, which lases above 1.6 μm and (on a different transition) at 2.94 μm.

Another solution to the high threshold and low efficiency problem is to operate on the $^4S3/2$ to $^4I9/2$ transition in erbium. This results in wavelengths generally in the 1.66 to 1.78 μm region, depending upon the host material. For these transitions the terminal level is well above the ground level and a four-level lasing scheme exists. The best host materials for this transition have been YLiF4 (YLF) and YAlO3 (YALO), but many others have been reported.

The Er:YLF lasers appear most promising for this transition. The YLF host [3] has good ultraviolet transmission for the high absorption bands located above the upper lasing level. In addition, the upper level of erbium in YLF favors a proper single lasing transition much more so than does glass hosts which exhibit multiphonon relaxation processes.

The major transition of importance in Er:YLF is at 1.73 μm, a region considered eyesafe. (Other transitions at 0.85 and 1.23 μm are not eyesafe, and so are not considered here). The 1.73 μm wavelength is quite fortunate, as it allows good atmospheric transmission in a spectral region bounded by water absorption bands on both sides.

A recent report [3] by experimenters who have investigated Er:YLF for a number of years indicate the following performance level: 25 mJ (Q-switched) for an electrical pump efficiency of 0.11% and pulselengths of 50 ns. (It should be noted that Nd:YAG systems can demonstrate 1-2% efficiency or better under similar conditions.)

If an Er:YA103 laser [14, 24] is operated on the same transition lines as described above, then lasing action occurs at 1.663 μm, which is also an important line for eye-safety and other applications. This lasing medium has been extensively investigated by several sources, and researchers appear to be divided as to their choice between YLF and YALO host materials.

Recent experiments [11] have resulted in three new wavelengths (1.667, 1.706, and 1.729 μm) being observed in Er:YA103 from the same basic transitions listed above. These lines have been explained by the fact that the upper state is actually a manifold split into two Stark levels, and the lower state is split into five Stark levels. This splitting allows ten possible laser transitions, only four of which have been observed at this time. The additional lines were observed by inserting wavelength tuning elements in the resonator such as etalons or prisms. Although of scientific interest, these additional higher threshold lines will probably not be selected for eyesafe applications unless some additional advantage (e.g. improved atmospheric transmission) is identified.

Erbium lasers suffer another serious disadvantage when compared to neodymium lasers in that high repetition rates are generally not possible. The Er:glass lasers, in a three-level scheme, are particularly difficult to operate at higher rates. High threshold pumping levels lead to considerable thermal birefringence and lensing effects in the rod. Even if lasing can be maintained at modest repetition rates, the beam quality is seriously degraded.

Operation of a Q-switched Er:glass laser at a 5 Hz rate has been reported [22]. This was obtained by proper glass selection, use of both Yb and Nd sensitizers, operation at near-threshold conditions, and strict stabilization of the rod temperature by liquid cooling. The electrical pumping efficiency was very low, on the order of 6 mJ for 120 J pump energy, or 0.005%.

Erbium lasers in YLF and YALO operating on the four-level scheme can produce repetition rates of perhaps 10 Hz or more. However, the very low efficiencies that are realized usually prohibit operation at these rates, due to power supply limitations, excessive cooling requirements, or thermal distortions in the laser rod.

It is concluded that erbium lasers will normally be used only for low pulse rate applications and where input power is not a problem.

C. Holmium Lasers

The very poor efficiency of erbium lasers has provided impetus to the investigation of holmium [8], which can be as efficient as neodymium. The transition of most interest is the $^5I7$ to $^5I8$ transition which lases near 2.1 μm.

Holmium lasers have been demonstrated in YLF [9, 14], YAG [9, 13], YAlO3, and many other host materials [19]. Other lasing transitions of lesser importance have also been observed.

Holmium lasers also benefit from sensitizers such as Cr^{3+}, Tm^{3+}, Er^{3+}, Yb^{3+}, and multi-dopant (alphabet) combinations which have surely taxed the crystal growing art. When efficiencies as high as 4% were reported in 1972 [13] and 6.5% in 1975 [14], interest was high.

Unfortunately, there is also a serious flaw with holmium lasers. Due to a three-level lasing scheme with a terminal level near the ground level, holmium lasers must be operated at cyrogenic temperatures to obtain high efficiencies. Many investigations have been conducted at liquid nitrogen (77 °K) temperatures, and in comparison room temperature results are not nearly as attractive. A relatively recent report, for example, gives a slope efficiency of only 0.22% for sensitized Ho:YLF at room temperature [14].

The longer wavelengths of holmium (as compared to erbium) lasers have been a disadvantage, due to restrictions on detector availability in this infrared region. This subject is covered in Section IV. It can be concluded that holmium lasers will find much less usage than will erbium for eyesafe communication systems.

III. RAMAN SHIFTED LASERS

There are techniques which can be used to generate eyesafe wavelengths, using solid-state or other lasers whose outputs are not in the desired spectral region. A number of nonlinear techniques can generate additional spectral lines through harmonic generation, stimulated Raman scattering, stimulated Brillouin scattering, and other nonlinear mixing processes. In this section emphasis is placed on one particular stimulated Raman process which has exhibited excellent results in generating 1.54 μm radiation at high conversion efficiencies.

A. The Raman Effect

The spontanous Raman scattering process has been investigated since the late 1920's and early 1930's [5]. An incident photon of one frequency passes through a suitable material and is "scattered" into a photon of different frequency. Due to conservation of energy principles, the difference in energy (proportional to the difference in frequency by Planck's constant) is absorbed by the medium. This results in vibrational, rotational, or electronic excitation of the medium. It is the molecular construction of this Raman medium that determines the difference frequency of absorption.

The by-product of this process, the scattered photon, has a frequency known as the Stokes frequency which is smaller (longer in wavelength) than the initial incident photon [2]. (It is also possible to produce so-called "anti-Stokes" frequencies of higher energy than the incident photon, if the absorbing medium is in an excited state before the Raman process occurs.)

The stimulated Raman effect was accidentally discovered by Eric Woodbury and Won Ng in 1962, while investigating the ruby laser during its infancy. The effect is the same as for spontaneous Raman generation, except that concentrated incident laser radiation produces many more scattered and stimulated photons at the Stokes frequency. The scattered radiation is coherent in nature and exhibits many of the excellent qualities, such as directionality, of a laser beam. With proper gain, sufficient path length, and/or reflective feedback, an efficient Raman laser is achieved [4, 15].

Many different materials have been investigated for the Raman effect, including solids, liquids, and gases. One particularly promising effect for eyesafe applications is covered in the next section.

B. Raman Conversion in CH4

Reviewing the disadvantages of erbium, holmium, and ruby lasers discussed in Section II, a desirable eyesafe laser would have attributes more like a Nd:YAG laser, including an acceptable (but unfortunately low) pump efficiency, a highly advanced state of development, and readily available optical components such as Q-switches, polarizers, laser rods, etc. Indeed, it is a consequence of the excellent qualities of the Nd:YAG laser that make it a worthy choice as a pump laser for input to Raman conversion systems.

In Section I it was noted that the 1.54 μm wavelength from an Er:glass laser, due to extensive investigation by the medical and safety field, has been granted an exceptionally large permissible exposure level that is 100 times larger than for other wavelengths in the same spectral region. Because of this quirk in present safety standards, it is obviously desirable to have an eyesafe laser at this singular wavelength. Fortunately good atmospheric transmission occurs here and suitable photodetectors are available, as will be covered in Section IV.

Recent work on eyesafe lasers at a number of locations has concentrated on a particular Raman conversion [6, 7, 17] in high-pressure methane gas (CH_4). The simplest of hydrocarbons, methane is colorless and odorless and exhibits good optical properties at high pressures. One undesirable feature, flammability, can be controlled.

A methane Raman gas cell, if pumped by a Nd:YAG laser at 1.06 μm, produces a first Stokes frequency at 1.54 μm, the ideal wavelength for eyesafe operation. Typically the gas cell is pressurized to 800-1000 psig [7] for efficient conversion and subsequent relaxation of excited methane molecules. Conversion efficiencies of 30% or more are possible with linear slope efficiencies above 50% once the threshold for conversion is reached. (Maximum theoretical conversion efficiency is the ratio of the input to output wavelengths, or 69%).

In the Raman cell the incident laser beam is focused to a small size to produce the high intensities necessary for significant conversion. The cell may be mounted with mirrors for multiple-pass gain. The exit aperture also has a short focal length positive lens to recollimate the frequency shifted beam.

The emerging beam will not be spectrally pure. Some unconverted 1.06 μm radiation will be present, and typically some shorter Stokes frequencies and longer anti-Stokes frequencies (some of which may be visible) will appear. These extraneous wavelengths can be easily removed by glass or plastic absorption filters, beamsplitters, prisms, or dichroic filters.

Since the difference in energy between the incident pump photons and exiting Raman shifted photons is absorbed by the methane, heating of the gas occurs. This heat is dissipated by collisions between the molecules and the walls of the container. At low repetition rates of the laser, the excess heat is easily removed. At repetition rates above 5 Hz (depending upon gas cell size), heating of the gas will result in significant thermal distortion and the exiting beam will be seriously degraded. This problem is easily resolved by circulating the gas with an internal blower. Rates as high as 60 Hz [7] have been so demonstrated.

Lifetimes do not appear to be a problem with the methane gas cell, particularly when fitted with hard seals and operated in a circulating mode. At higher input levels additional nonlinear effects such as stimulated Brillouin scattering, second Stokes lines, anti-Stokes lines, and arcing may occur. The addition of 5% of argon gas has been used to help stop the Brillouin scattering [6]. Optimum focusing of the input beam will reduce arcing problems, and the input laser intensity may be attenuated to match the cell size and geometry for best conversion.

The pulsewidth of the Raman shifted wavelength will be shorter than that of the pump laser. Since the Raman conversion does not occur below a threshold point, the Raman pulsewidth is shortened on both leading and trailing edges as compared to that of the pump laser. A 22 ns pulse from the Nd:YAG laser may result in a 17 ns Raman pulse, for example [7].

Recent successes with Raman methane gas cells are leading to several eyesafe applications, to be reviewed in Section V.

IV. DETECTORS FOR THE NEAR INFRARED

An important element of any laser communication system is the photodetector which, with suitable optics and filters, forms the front end of the receiver. The ideal detector would have the following qualities: high sensitivity and responsivity at wavelengths of interest, low noise and leakage currents, low capacitance for high-speed response to narrow Q-switched laser pulses, and good sensitivity over temperature extremes without the necessity for cryogenic cooling. Additionally, the ideal detector would be immune to optical and vibrational damage, be readily available in large active areas, and be low in cost.

At least two types of detectors meet most of these requirements in the eyesafe region. In the following sections these detectors are compared to silicon detectors which are standard for visible and near infrared laser detection at shorter wavelengths.

A. Silicon Detectors

Silicon detectors are widely used in laser receiver systems at visible and infrared wavelengths up to 1.06 μm, the primary wavelength of Nd:YAG lasers. Spectral response peaks in silicon well below this wavelength, but a number of manufacturers have developed specially enhanced detectors particularly for use with Nd:YAG lasers. Unfortunately the bandgap of silicon limits its use at much longer wavelengths, and operation at eyesafe regions above 1.4 μm is impossible. However, a brief discussion of the attributes of silicon serves as a reference for comparison of longer wavelength detectors.

Silicon detectors are available in a variety of configurations to meet each of the requirements of the ideal detector listed previously. In addition, to the standard p-i-n photodiode configuration which may be operated in photovoltaic or photoconductive modes, silicon avalanche detectors are available with internal gains up to 150. Internal preamplifiers, quadrant and array configurations, internal spectral filters, fiber optic interfaces, and other options are in the commercial market. For narrow field-of-view (FOV) applications not requiring large active areas (such as rangefinders), silicon avalanche detectors are widely employed. For other applications requiring large FOV and high sensitivity, large area detectors are easily fabricated in single and multiple element configurations.

The excellent characteristics of silicon detectors will be difficult to match in longer wavelength materials.

B. Germanium Detectors

For many years germanium photodiodes were the only logical choice for high-speed detectors up to 1.8 μm, at wavelengths longer than could be detected by silicon. The spectral response peaks near 1.5 μm, so germanium detectors are compatible with Er:glass and Raman shifted lasers at 1.54 μm. Germanium is marginally suitable for Er:YLF and Er:YALO laser detection up to 1.73 μm, but is not suitable for use with the prominent Ho:YLF laser transition. The spectral response of germanium, compared to other detectors of interest, is shown in Figure 1. (Note that the peak response has been normalized to unity for each detector.)

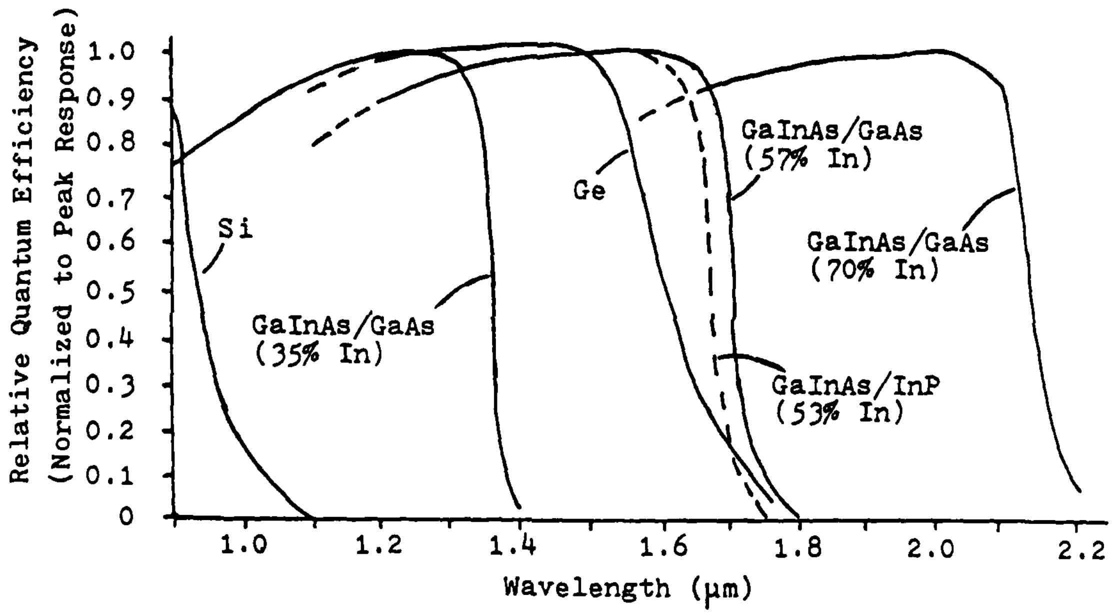

Figure 1. Near infrared spectral response of photodiodes [21].

Germanium photodiodes have some serious drawbacks compared to silicon. Noise is much higher, as well as sensitivity to operating temperature. In addition, responsivity is lower and dynamic impedance is worse. Avalanche detector configurations in germanium have not been too successful and gains are much lower due to excess noise created by the avalanche process [21].

Germanium detectors are available in a variety of packages with active areas up to 5 mm. Both photovoltaic and photoconductive modes of operation are possible.

C. InGaAs and InGaAsP Detectors

In very recent years a new class of detectors from various alloys of the III-V elments has been developed. The most commonly used alloy material is GaInAs, epitaxially grown on GaAs substrates or on InP substrates [21]. Figure 1 shows the spectral response characteristics of several different alloy compositions for which the percentage of indium has been varied.

The impetus for developing these detectors has been the fiber optic communications field. Optical fibers have demonstrated very low absorption losses at 1300 nm (<0.5 dB/km) and 1550 nm (<0.2 dB/km) [23]. Since the latter wavelength closely matches the Er:glass and Raman shifted Nd:YAG laser wavelength, eyesafe laser receivers also benefit from advances in the detector technology.

Detectors made of InGaAs and InGaAsP are superior to germanium in many key parameters such as quantum efficiency and noise equivalent power. Table 2 is a performance comparison of several detector parameters. The InGaAsP detectors may be superior at shorter wavelengths such as 1.54 μm, but are probably not suitable for use with Er:YLF lasers and are definitely incompatible with holmium lasers.

TABLE 2. Comparison of InGaAs and Ge Detectors [23]

(2 mm ACTIVE DIAMETER: NO BIAS, 25 °C)

Parameter	InGaAs	Ge
Responsivity (A/W)		
0.82 μm	0.2	0.1
1.3 μm	0.8	0.5
1.55 μm	0.9	0.7
Quantum Efficiency (%)		
1.3 μm	80	50-60
Dynamic Impedance (Kohms)	200	6
NEP (pw/Hz$^{1/2}$)	0.3	2.4
Capacitance (pF)	600	1600
Max. Operating Temp. (°C)	100	60

The same detectors are also useful at 1.06 μm, the wavelength of Nd:YAG lasers. It is therefore practical in some situations to build a dual wavelength laser receiver which can detect the normal and Raman shifted laser wavelength.

Active area sizes have been quite limited until the last year, but sizes up to 3 mm in diameter are now on the market. Experimental avalanche detectors with gains on the order of ten are also available, with lower noise levels than with germanium. The extensive research ongoing in InGaAs materials for both detectors and solid-state emitters will undoubtedly lead to further advances in the near future.

V. APPLICATIONS

Eyesafe systems using solid-state lasers have been recently developed for several commercial and military applications.

- In 1980 Hughes Aircraft Company [6] reported development of a cloud height indicator for the Federal Aviation Administration, using a Raman shifted Nd:YAG laser at a wavelength of 1.54 μm. The germanium detector sensed reflections from the bottom layer of overhead clouds.

- In 1982 Sanders Associates [18] developed a similar device using an Er:YLF laser at 1.73 μm and a germanium detector. An Er:YLF laser rangefinder was also reported.

- KEI, Inc. [16, 17] has developed handheld and larger military rangefinders using Er:glass lasers at 1.54 μm and III-V detectors. A recent development was for the U. S. Army's Mini-Eyesafe Laser Infrared Observation Set (MELIOS).

- Hughes Aircraft Company [6, 7] has developed a handheld laser rangefinder using a Raman shifted Nd:YAG laser, also for the MELIOS program. Other companies such as Litton Laser Systems and Ferranti, Inc., are also pursuing this technology. Detectors made of III-V alloys are now clearly better than germanium for such applications.

- KEI is now developing an Er:glass system to simulate pulses from a Nd:YAG laser designator for training purposes, as part of the U. S. Army's MILES/AGES II program. (The newer detectors are not presently suitable for use in laser semiactive guided missiles, primarily due to limitations in size and FOV.)

- Eye safety is not the only reason for pursuing these lasers. Er:glass lasers [22] and Raman shifted Nd:YAG lasers [10] are being investigated as potential sources for location of faults in sections of optical fibers more than 100 km long.

Even more applications are anticipated for the future.

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